THREE-DIMENSIONAL STRUCTURES OF CHONDRULES AND THEIR HIGH-SPEED ROTATION. A. Tsuchiyama[1], R. Shigeyoshi[2], T. Kawabata[1], T. Nakano[3], K. Uesugi[4] and S. Shirono[5], [1] Department of Earth and Space Science, Osaka University, 1-1 Machikaneyama-cho, Toyonaka 560-0043, JAPAN, akira@ess.sci.osaka-u.ac.jp, [2] Graduate School of Science and Engineering, Kagoshima University, Kagoshima 890-0065, JAPAN, Institute of Geoscience, [3] National Institute of Advanced Industrial Science and Technology, Tshukuba, 305-8567 JAPAN, [4] Japan Synchrotron Radiation Research Institute, Mikazuki, 679-5198 JAPAN, [5] Graduate School of Environmental Studies, Nagoya University, Nagoya 464-0814, JAPAN.

Introduction: Three-dimensional structures of chondrules have been studied using X-ray microtomography. The following results were obtained from the studies. (1) Voids are present in chondrules [1,2]. (2) Olivine has platy morphology in barred olivine (BO) chondrules [2]. (3) Pyroxene has acicular of platy morphology in radial pyroxene chondrules [3]. (4) Chondrules with oblate shapes are present [2]. (5) Voids seem to concentrate near the short axis of an oblate chondrule [2] (6) Olivine plates are normal to the short axis of an oblate BO chondrule [2]. Tsuchiyama et al. [2] proposed from the results of (4)-(6) that chondrules were rotating with high speed during their formation. However, as they examined only three chondrules, statistical study is required to confirm rotating chondrules.

Experiments: Forty-seven chondrules separated from the Allende meteorite (CV3) were used in the present experiments. They were imaged with an X-ray microtomography system using synchrotron radiation at BL20B2 in SPring-8, Nishiharima, JAPAN (SP-μCT [4]). The chondrules were mounted into cylinders of epoxy (about 3mm in diameter) to reduce artifacts of CT images and to reserve the CT slice directions, and imaged with monochromatic beams at 18-25 keV. Cross-sectional images (CT images) were reconstructed from 300-360 projections with a convolution back projection algorithm. Three-dimensional structures were reconstructed by stacking successive CT images with the voxel size of $5.83\times5.83\times5.83\,\mu$m, which gives the spatial resolution of about 13 μm [4].

The three-dimensional structures of the chondrules showed that some were compound chondrules and some were imperfect in their shapes. Twenty chondrules with perfect shapes and smooth surfaces were selected for further analysis. Three chondrules used in the previous study [2] were also included in this analysis. Some chondrule samples have Fe-rich fine–grained rim (or matrix) on the surfaces. They were identified by image analysis using appropriate thresholds of CT-values, which are quantitative expressions of CT image contrast, and the external shapes without the rims were obtained. Enlarged three-dimensional plaster figures of some chondrules were formed by rapid prototyping method to examine the external shapes in more detail. Metal and/or sulfide grains and voids inside the chondrules were also identified by image analysis and their three-dimensional distributions were obtained.

Some chondrules were thin-sectioned as parallel as possible to the sliced directions of the CT images. The thin sections were observed under a polarized optical microscope and a scanning electron microscope (SEM) to confirm the presence of Fe-rich rims (or matrices), metal/sulfide grains and voids.

Results: The external shapes were approximated as three-axial ellipsoids with a-, b- and c-axes (axial radii are A, B and C ($A\geq B\geq C$), respectively) using the moments of inertia of the chondrules, where the rotation axes with the minimum and maximum moments correspond to the a- and c-axes, respectively. The aspect ratio, p, was defined as C/A. The degree of oblate or prolate shape is defined as follows: $C/B=(B/A)^n$ and $\log(n)\rightarrow\infty$ and $-\infty$ for oblate and prolate shapes, respectively. The plot of C/B vs. B/A (Fig.1) showed that (1) the shapes are diverse from oblate ($A\sim B>C$: $\log(n)>>0$), general three-axial ellipsoid ($A>B>C$) to prolate chondrules ($A>B\sim C$: $\log(n)<<0$) and (2) two groups can be recognized: oblate to prolate chondrules with large p of 0.85-0.98 (group-A) and prolate chondrules with small p of 0.74 to0.78 (group-B).

Eighteen and nineteen chondrules out of twenty contain metal/sulfide grains (up to 6.8 vol.%) and voids (up to 2.9 vol.%), respectively. If oblate chondrules were formed by rotation during melting, heavy metal/sulfide grains and light voids should be moved away from and toward the short axis (c-axis), respectively, due to the centrifugal force. To express distributions of metal/sulfide grains and voids with respective to the c-axis quantitatively, the moments of inertia of metal/sulfide grains or voids around the c-axis, M, were obtained and compared with those of random distribution, Mr. If the degree of oblate is sufficiently large ($\log(n)>0.2$), M/Mr>1 for metal/sulfide indicating concentration of these grains toward the surface from the c-axis and M/Mr<1 for voids indicating concentration of voids toward the c-axis. The present results strongly suggest that the oblate chondrules were rotating during chondrule formation.

Discussion: We can estimate rotation rates for the oblate chondrules by assuming that these flat shapes were equilibrium shapes, where the centrifugal force was balanced with the surface tension of a chondrule melt [5]. In this case, the shape and thus the aspect ratio, p, are determined uniquely by the parameter, Σ:

$$\Sigma=\rho A^3\Omega^2/8\gamma, \qquad (1)$$

where ρ is the density of a chondrule melt, Ω is the angular velocity and γ is the surface tension. The plot of A vs. p for the oblate chondrules is shown in Fig.2. This shows the rotation rate of about 50 to 350 rps. The rotation rate should be reduced by molecular viscosity of surrounding gas in the time scale of 10-10000 sec [6]. As the chondrule shapes were determined at the time of solidification and the cooling time scale for choendrule formation is the order of 10000 sec, the rotation rate should be higher and the aspect ratios should be smaller during melting. If Σ exceeds the critical value of 0.844 (p>0.490), the rotating melts become unstable [5] and should split into small pieces. The lower limit of the aspect ratio of about 0.85 (Fig.2) might correspond to this critical aspect ratio (0.490) during melting.

If the prolate chondrules were also rotating, the stable axis for the rotation was the short axis (c-axis). The prolate chondrules with large aspect ratios (group-B in Fig.1) can be explained by spitted droplets due to the shape instability, where Σ exceeds the critical value. If this is the case, the upper size limit of chondrule can be explained by the high-speed rotation. The general three-axial ellipsoids and prolate chondrules with small aspect ratios in group-A (Fig.1) should be formed by some modification during solidification and/or precession during rotation.

High-speed rotation of molten chondrules largely constrains their formation process. This is possible by the shock wave model [7] or impact model. The shock wave model may be favorable because the impact model has a problem about energies to make molten droplets by collision of planetesimals [8].

Most of the chondrules imaged in this study have voids. This shows that voids are important constituents of chondrules as well as silicates and metal/sulfides although their amounts are small (less than 3 vol.%). Three-dimensional distribution of voids in an oblate BO chondrule suggests that the voids were formed by bubbling due to increase of the concentration of volatile components in a melt by olivine crystallization.

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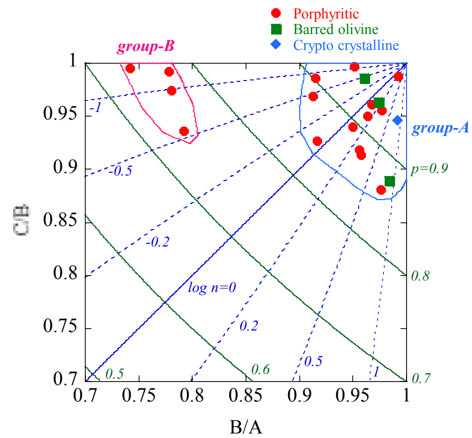

Figure 1. Chondrule shapes approximated as three-axial ellipsoids with the axial radii of A, B and C (A≥B≥C). The aspect ratio, p=C/A, and the degree of oblate or prolate shape (log(n)→∞ and -∞ for oblate and prolate shapes, respectively) are shown. Chondrule textures are also shown.

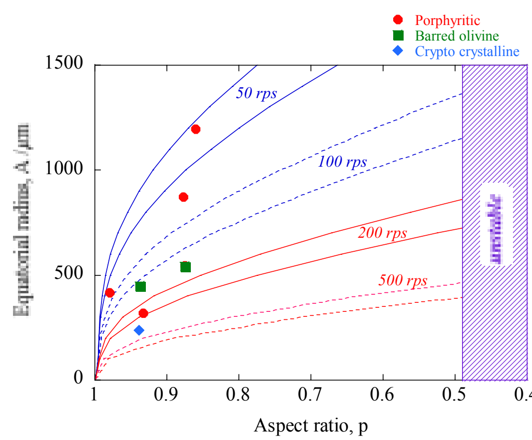

Figure 2. The equatorial radius of chondrules, A, plotted against the aspect ratio, p, for oblate chondrules. The rotation rates were calculated from Eq.(1), where the upper and lower limits of the surface tension, γ, for basalts at 1000-1500°C (250 and 420 dyn/cm) [9] were adopted.